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Flue Gas Desulfurization Pilot Study. Phase I Survey of Major Installations. Appendix 95-A Limestone/Sludge Flue Gas Desulfurization Process

NATO Committee on the Challenges of Modern Society, Brussels (Belgium)

Jan 79

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COMMITTEE ON THE CHALLENGES
OF MODERN SOCIETY

PB 295002

Flue Gas Desulfurization Pilot Study Phase I — Survey of Major Installations - Limestone/ Sludge Flue Gas Desulfurization Process

Appendix 95-A

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NATO-CCMS STUDY

PHASE I

Flue Gas Desulfurization Pilot Study Phase I

Survey of Major Installations - Limestone/ Sludge Flue Gas Desulfurization Process

APPENDIX 95-A

Lead Country - United States

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TABLE OF CONTENTS

		Page
SUMMARY		v
1.0	BACKGROUND AND INTRODUCTION	1-1
2.0	GENERAL PROCESS DESCRIPTION	2-1
	2.1 Process Chemistry	2-1
	2.2 Description of Equipment Components	2-5
	2.3 Operating Parameters	2-14
3.0	CURRENT STATUS, ASSESSMENT, AND PLANS	3-1
4.0	RECENT TECHNOLOGICAL DEVELOPMENTS AND SOLUTIONS TO PROBLEM AREAS	4-1
	4.1 Recent Technological Developments	4-1
	4.2 Solution of Problem Areas	4-3
5.0	COST	5-1
6.0	BIBLIOGRAPHY	6-1
APPENDICES		
	A. Questionnaire Data	A-1
	B. Availability Factor Computation	B-1
	C. Conversion Factors	C-1

LIST OF FIGURES

No.		Page
1	Example Flow Diagram and Material Balance of a 500-MW Coal-Fired Boiler and Limestone Sludge FGD System	2-2
2	Spray Tower	2-7
3	Sieve or Perforated Tray Absorber	2-8
4	Mobile Bed Scrubber	2-9
5	Fixed Packing Absorber	2-10
A	Flow Diagram La Cygne FGD System	A-18
B	Process Flow Diagram of the FGD System at The Cholla Power Plant	A-19
C	Scrubber Module at Sherburne	A-20
D	Sherburne County Wet Scrubber System	A-21

LIST OF TABLES

No.		Page
1	Summary of Status of Surveyed FGD Systems Limestone/Sludge	3-3
2	Status of Surveyed Installations Limestone/ Sludge Process	3-4
3	Cost Data of Individual Installations for the Limestone/Sludge FGD System	5-3

SUMMARY

Limestone/sludge systems are the least expensive of all flue gas desulfurization (FGD) systems currently used in the United States. Limestone is cheap and generally locally available, as is the land necessary for sludge disposal. Limestone/sludge systems require 200,000 m^2 at small plants and as much as 4,000,000 m^2 at large plants for sludge disposal. In other countries, limestone appears to be available in sufficient quantities to make it inexpensive, but space for sludge disposal is generally not as available as in the United States.

The process is well developed chemically, but mechanical problems are still encountered in certain facilities. These problems include: fan vibration; pump and pipe erosion; scale buildup in the scrubber, demister, and reheat sections; potential pollution in open-water systems; and corrosion and erosion. Essentially all these problems have been solved at particular installations. The similar limestone/gypsum systems in Japan offer the best examples of well-designed and well-operated limestone systems. Rapid response to changing boiler rates and flue gas conditions is

essential in all limestone systems, and only highly trained chemical technicians or well-designed automatic controls can make the changes fast enough. The Japanese have succeeded in developing these automatic process controls on their limestone/gypsum systems.

The system operates well on large boilers fueled with either coal or oil. On small systems with low operating factors, labor and capital charges can be a limiting factor. Strict solid waste and water regulations either in force or imminent could necessitate more careful consideration of sludge disposal approaches. It may be necessary to incorporate an oxidation step and/or employ sludge stablization/fixation to produce acceptable materials for landfill disposal.

The advantages and disadvantages of the limestone sludge systems are as follows:

Advantages

(1) The basic process is fairly simple and has few process steps.

(2) Capital and operating costs are relatively low, and reserves of limestone are fairly abundant.

(3) SO_2 removal efficiencies can be as high as 95 percent.

(4) The two-stage treatment of flue gases permits removal of SO_2 and particulates.

(5) Many years of operating experience have led to a greater understanding of the basic principles of this process.

(6) The process has demonstrated successful performance, especially in the removal of SO_2 from coal-fired systems.

(7) Fly ash does not adversely affect the system.

Disadvantages/problems

(1) Large quantities of waste must be disposed of in an acceptable manner.

(2) If not designed carefully or operated attentively, limestone systems have a tendency toward chemical scaling, plugging, and erosion. These problems can frequently halt operation of the system.

(3) The scrubber requires high liquid-to-gas (L/G) ratios necessitating large pumps with attendant electrical requirements.

(4) The sludge may have poor settling properties when it has high sulfite content. Forced oxidation or soluble Mg in the slurry have been shown to lower sulfite content.

1.0 BACKGROUND AND INTRODUCTION

This report is one of a series on the status of flue gas desulfurization (FGD) processes in the NATO countries and Japan. The United States, the Federal Republic of Germany, and Norway have acted as lead countries in gathering information and preparation of the reports.

The limestone/sludge process is a wet scrubbing system in which a mixture of finely crushed limestone ($CaCO_3$) and water is intimately contacted with the boiler flue gases in an absorption tower. The SO_2 in the flue gas reacts with the limestone to form calcium-sulfur compounds. The resulting solids are separated from the liquid and disposed of in a sludge pond.

Limestone scrubbing of flue gases evolved from early attempts to use water as the scrubbing medium. It was discovered that dissolved alkaline carbonates, which occur naturally in water, were increasing scrubbing efficiency. This led to the addition of limestone to the scrubbing water.

One of the first efforts to use limestone slurry to clean boiler flue gases was made in 1933 at the coal-fired

Battersea Power Station in London, England. The London Power Co. had studied water and limestone scrubbing systems extensively before the Battersea unit was installed. This unit scrubbed the gas with a countercurrent spray of chalk ($CaCO_3$) slurry and water. The scrubber unit was a timber-lined brick tower. The sludge was diluted with water from the River Thames and then dumped back into the river. In 1952, this type of FGD system was installed on the oil-fired Bankside Power Station in London.

Another early example of a limestone sludge FGD system was the Howden ICI process installed in 1936 on a coal-fired power station at Fulham, England. This scrubber was a fixed packed-bed unit. The waste product (sludge) from this system was calcium sulfate (gypsum), which was barged down the River Thames and dumped into the North Sea.

All three of these early systems reported at least 90 percent SO_2 removal. The Battersea unit operated until 1973 (except during World War II), the Bankside unit is still operating, and the Fulham Station was shut down in 1940.

In the United States, the Tennessee Valley Authority (TVA) performed bench scale and pilot plant studies in the 1950's, the first known work in this country. In 1965, Universal Oil Products established a pilot plant in Wisconsin to develop its own scrubber system, and the following

year Combustion Engineering followed suit. Commonwealth Edison, Chicago, Illinois, put the first full-scale U.S. unit into operation in 1972 at the Will County Station. In Japan, there are many limestone systems in operation. Although all of them by-produce gypsum rather than a disposable sludge, they do not differ greatly from the limestone/sludge system. There are currently 13 limestone/sludge systems in operation worldwide, representing 5640 MW of generating capacity. Twelve are in the United States and one in the United Kingdom.

The addition of soluble magnesium compounds to the scrubber liquor has been shown to reduce scaling while increasing the SO_2 removal efficiency of lime systems; this technology now is being applied to limestone systems.

2.0 GENERAL PROCESS DESCRIPTION

The principles of all limestone scrubbing systems are essentially the same. When the limestone-water slurry comes in contact with flue gas containing SO_2, the SO_2 is absorbed into the slurry and reacts with the limestone to form an insoluble sludge. The by-products include gypsum ($CaSO_4 \cdot 2H_2O$) and calcium sulfite hemihydrate ($CaSO_3 \cdot 1/2\ H_2O$). These sludge by-products are generally disposed of in a pond. Figure 1 is an example of a flow diagram and material balance of a 500-MW, coal-fired boiler with a limestone/sludge FGD system.

2.1 PROCESS CHEMISTRY

The overall reactions that take place in the absorber are

$$SO_2 + CaCO_3 \rightarrow CaSO_3 + CO_2 \quad (1)$$

$$SO_3 + CaCO_3 \rightarrow CaSO_4 + CO_2 \quad (2)$$

Many intermediate steps also take place, however. The calcium ion is formed during slurry preparation.

$$CaCO_3(s) \rightarrow CaCO_3\ (aq) \quad (3)$$

$$CaCO_3 + H_2O \rightarrow Ca^{++} + HCO_3^- + OH^- \quad (4)$$

The SO_3 anion forms at the flue gas-slurry interface in the absorber.

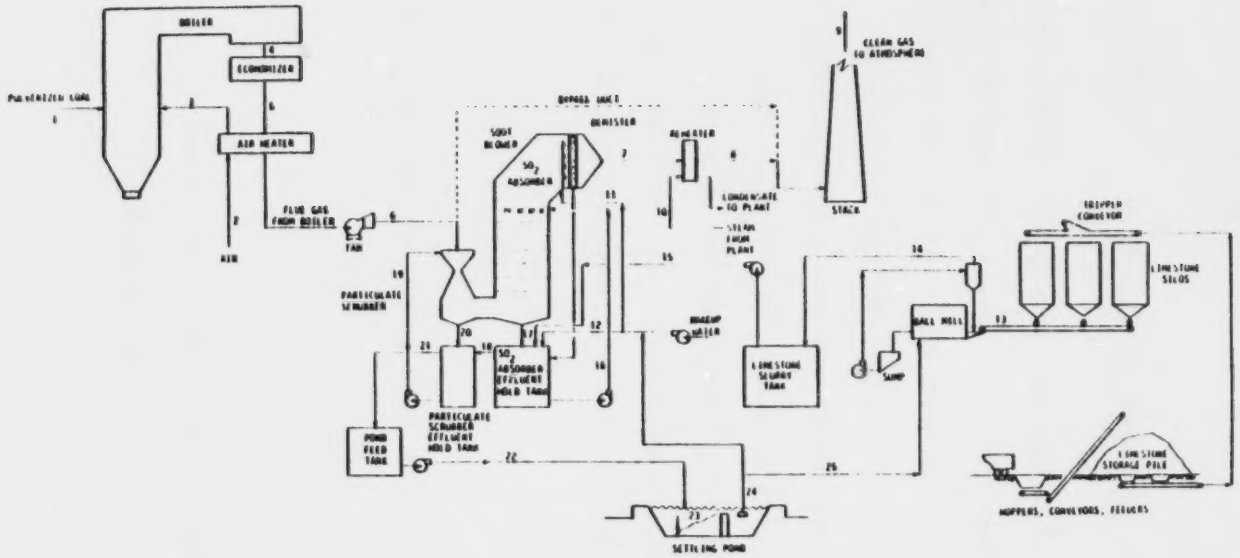

Figure 1. Example flow diagram and material balance of a 500-MW coal-fired boiler and limestone sludge FGD system.

(Based on Tennessee Valley Authority report, "Detailed Cost Estimate for Advanced Effluent Desulfurization Process.")

(continued)

Stream no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Description	Coal to boiler	Combustion air to air heater	Combustion air to boiler	Gas to economizer	Gas to air heater	Gas to particulate scrubber	Gas to reheater	Gas to fan	Gas to atmosphere	Steam to gas heater	Makeup water to SO_2 absorber	Pond water to hold tank	Limestone to weigh feeder	Slurry to limestone slurry tank
Rate, 1000 kg/h	170	2049	1848	1998	1998	569.7	572.4	572.4	2290	7.98	36.9	35	11	18
Nm^3/s		401	371	394	394	109	121	121	485					
m^3/s liquid											0.010	0.010		0.003
Particulates, kg/h				15300	15300	3826	25.4	25.4	102					
Temperature, °C		411	278	477	374	154	51.7	72.8	79.4	241				
Specific grav.;														1.65
Viscosity, Pascal-second														
Undissolved solids, %														60
pH											See note 5			
Sulfur as SO_2 kg/h				11335	11335	11335	1134	1134	1134					

Stream no.	15	16	17	18	19	20	21	22	23	24	25
Description	Limestone slurry to hold tank	Recycle slurry to SO_2 absorber	SO_2 absorber slurry to hold tank	Overflow to hold tank	Recycle slurry to part. scrbr.	Part. scrbr. slurry to hold tank	Hold tank overflow to pond feed tank	Used slurry and fly ash to stg. pond	Settled used slurry and fly ash	Recycle pond water	Pond water to wet ball mill
Rate, 1000 kg/h	0.98	5439	5474	82	1234	1214	62.1	268	105	153	6.62
Nm^3/s											
m^3/s liquid	0.002	1.4	1.5	0.022	0.3091	0.3043	0.016	0.062	0.022	0.043	0.00184
Particulates, kg/h											
Temperature, °C				105			1.11		1.32		
Specific gravity											
Viscosity, Pascal-second											
Undissolved solids, %	7.2	-7.0		1.05			17		40		
pH							-5-5.5		See note 5	See note 5	
Sulfur as SO_2 kg/h							10202	10202	10202		

Notes:

1. Calculations based on:
   a. 120% stoichiometric limestone: 90% $CaCO_3$ (dry), 5% H_2O
   b. 3.5% sulfur in coal (dry)
   c. 12% ash coal (as fired)
   d. 92% of sulfur in coal evolves as SO_2
   e. 75% of ash in coal evolves as fly ash
   f. 99.5% removal of particulates to scrubber
   g. 90% SO_2 removal
   h. Pond evaporation and seepage equals rainfall
2. Particulates should be added to get total stream rate.
3. Stream numbers 6-8, 10-13, and 15-21 are each one of four similar streams.
4. Stream numbers 11, 14, and 25 are each one of two similar streams.
5. Rates for lines 11, 23, and 24 assume about one-sixth of pond life settled solids interstitial H_2O is put into pond start-up.

Reproduced from best available copy.

Figure 1 (continued).

$$SO_2(g) \rightarrow SO_2(aq) \quad (5)$$

$$SO_2(aq) + H_2O \rightarrow H_2SO_3^{=} \rightarrow HSO_3^{=} + H^+ \quad (6)$$

$$HSO_3^- \rightarrow H^+ + SO_3^{=} \quad (7)$$

The sulfite ion (equation 7) then combines with the calcium ion (equation 4) to form the precipitate calcium sulfite hemihydrate (equation 8).

$$Ca^{++} + SO_3^{=} + 1/2\ H_2O \rightarrow CaSO_3 \cdot 1/2H_2O(s)\downarrow \quad (8)$$

Gypsum, an additional precipitate, is formed as follows:

$$SO_3^{=} + 1/2\ O_2 \rightarrow SO_4^{=} \quad (9)$$

$$Ca^{++} + SO_4^{=} + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O(s)\downarrow \quad (10)$$

As reactions 8 and 10 proceed, the calcium cation is depleted from solution and additional $CaCO_3$ dissolves to react with the sulfite ion. In a limestone-sludge system, by-products occur from both reactions 8 and 10.

According to the molecular weights of limestone and SO_2, the theoretical requirement is 1 mol (100 g/mol) of limestone per mol of SO_2 (64 g/mol) removed. If a 20 percent excess stoichiometric amount and 95 percent purity of limestone are assumed, actual limestone required is

$$\frac{100}{64} \times \frac{1.2}{0.95} = 1.97 \text{ kg/kg of } SO_2$$

Dry sludge generated in the limestone process consists of calcium sulfite hemihydrate, carbonates, fly ash, and gypsum. Unused limestone and limestone impurities also combine with the sludge. The exact proportions of calcium

sulfite hemihydrate and gypsum depend on system design; but if equal proportions are assumed, the sludge generated can be calculated by considering molecular weights and adding the weights of limestone impurities and unused limestone.

$$\text{Dry sludge} = \frac{(0.5 \times 129) + (0.5 \times 172)}{64} + \frac{100 \times 1.2}{64 \times 0.95} - \frac{100}{64} = 2.76 \text{ kg/kg of } SO_2$$

When a venturi scrubber removes particulate matter, the particulates thus removed are also combined with the sludge. The final sludge to be disposed of contains at least 20 percent free water.

2.2 DESCRIPTION OF EQUIPMENT COMPONENTS

2.2.1 Primary Particulate Removal

The venturi scrubber is the first unit in most limestone FGD systems. This unit scrubs particulate from the gas; however, some SO_2 removal also occurs. The venturi scrubber has an advantage over an electrostatic precipitator (ESP) for particulate removal because the venturi cools and humidifies the flue gases before they enter the absorber section. A flue-gas cooler and humidifier must be used in connection with an ESP to cool the flue gases, generally to 50°C, prior to absorption. Moreover, if particulate is removed before the absorber, corrosion problems are reduced.

Booster fans are sometimes installed in series with the venturi to provide the power necessary to force the gas through the scrubber system.

2.2.2 SO_2 Absorber

The absorber is the primary SO_2 removal unit in the system. Each of the many available designs employs a different method to contact the flue gas with the slurry. The more common unit designs include fixed packing, mobile-bed packing (hollow or solid spheres), and horizontal or vertical spray towers. Figures 2-5 show schematic drawings of some of these designs. Although each unit performs differently, identical parameters have the same general effect on performance. Because of its simplicity, however, the spray tower is gaining popularity.

The scrubber must be constructed of materials that resist corrosion, erosion, and scaling. Scrubber bodies are fabricated of stainless steel or mild steel lined with an acid-resistant coating such as fiberglass-reinforced polyester (FRP), rubber, or glass flake. Scrubber internals are made of a variety of materials such as stainless steel, which has a tendency to pit; high nickel alloys, which are expensive; or FRP, which is fragile. No one material seems to stand above the others.

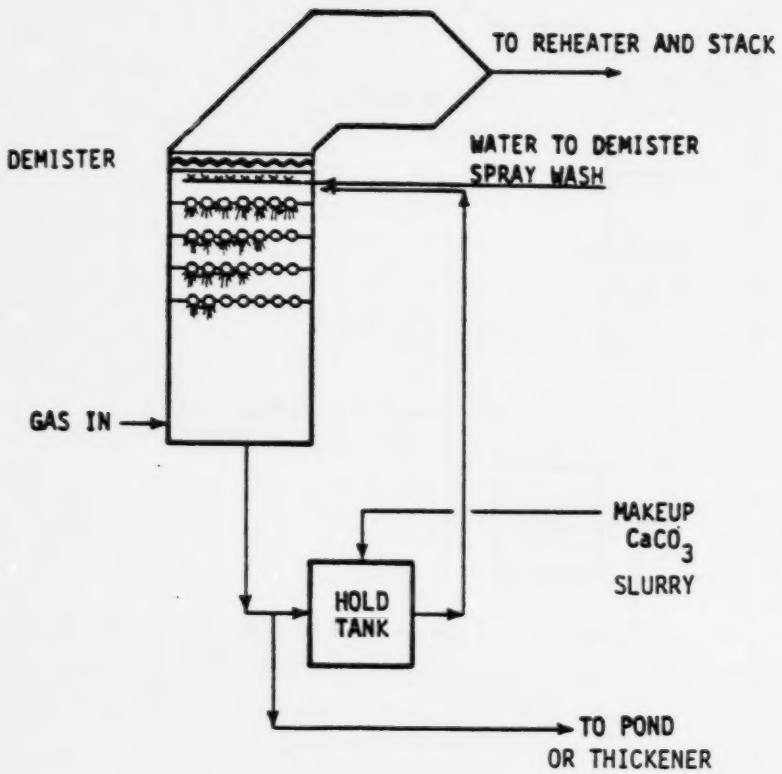

Figure 2. Spray tower.

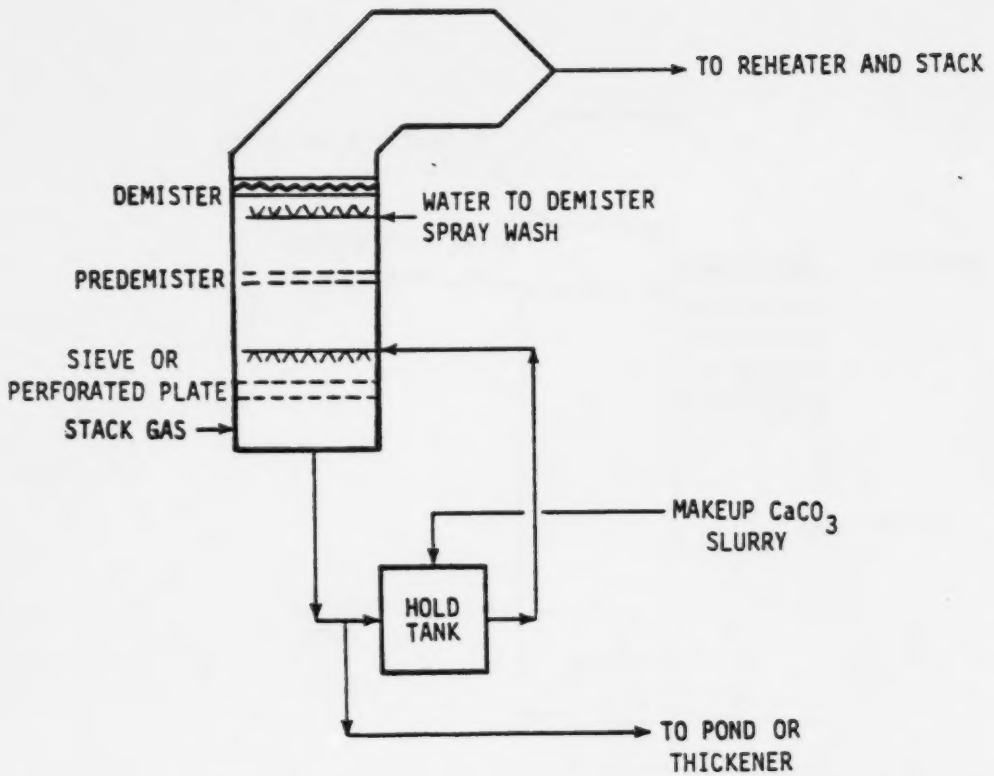

Figure 3. Sieve or perforated tray absorber.

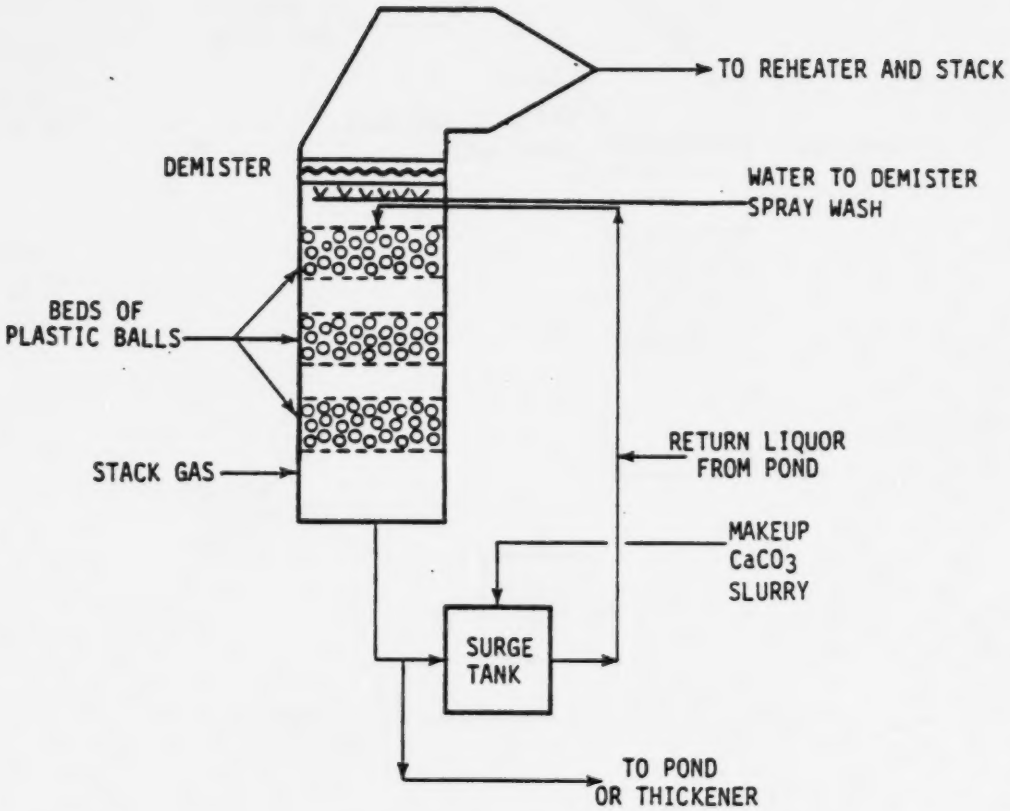

Figure 4. Mobile bed scrubber.

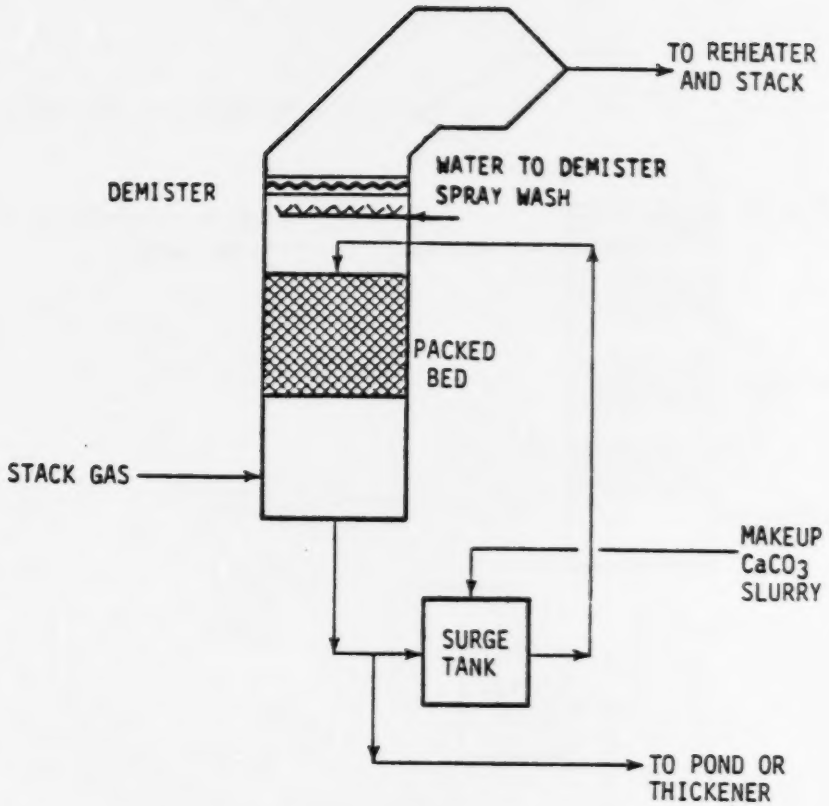

Figure 5. Fixed packing absorber.

The size and number of modules in a scrubber system are directly related to boiler size, turndown* requirements, system availability, and gas-liquid distribution. Boiler system loads fluctuate, and the scrubber system must change to maintain optimum scrubber performance. One method of adjusting to turndown is to shut down scrubber modules as the load decreases. The more modules in the system, the smoother the transition. Scrubber modules not being used can be scheduled for cleaning and maintenance during periods of low system load, thereby reducing overall scrubber down-time. The use of multiple modules also has the advantage of permitting the modules to be smaller. Smaller cross-section areas in the scrubber module promote uniform gas-liquid distribution and improve efficiency. Scrubber module sizes range from about 25 MW to 200 MW.

2.2.3 Demister

A demister is necessary to remove entrained droplets from the scrubber outlet gas to reduce downstream equipment corrosion and scaling and to reduce reheat requirements. Most of the droplets are large enough to be removed with a simple change in flue gas direction; this is provided by baffles. Two banks of demisters are usually sufficient, but

* Reduction in boiler output.

more can be added for additional demisting capability. Demisters are also subject to scaling and corrosion. Soot blowers or spray washes are installed to reduce this tendency, and materials of construction must be carefully selected.

Chevron and cyclonic-vane-type demisters are both effective. Although either can be operated in a horizontal or vertical position, the horizontal position predominates in the United States. Figures 2 through 5 show the demister in a horizontal position with vertical gas flow. There is much discussion pertaining to the advantages of each position, and a final selection depends on site-specific considerations.

2.2.4 Reheater

Reheating of stack gas is generally necessary to increase its bouyancy and reduce downstream corrosion. Thus, reheat not only helps meet ambient air standards; it also protects downstream equipment and prevents formation of acid mist. Reheating can be accomplished by installing a gas or low sulfur oil burner that exhausts directly into the stack, installing steam coils to heat the flue gas, injecting preheated air into the stack, or by-passing some hot flue gas around the FGD system directly into the stack (increasing emissions of SO_2). In-line heat exchangers are the most

popular because of their low initial capital cost, but they tend to corrode and scale. Soot blowers, better demisters, and better materials of construction reduce these problems.

2.2.5 Slurry Makeup

Limestone can be received in a crushed and milled state or can be crushed and milled on site. In the latter case, the limestone is ground (wet or dry) in a ball mill to a size not larger than 200-mesh and often finer than 325-mesh. Finer grinding reduces the amount of limestone that remains unreacted and would otherwise be disposed of in the sludge. Water is added until the solids content reaches 15 to 25 percent. The slurry is sent first to a feed tank, then to the absorber holding tank, where it is mixed with absorber effluent. The slurry from the absorber holding tank is pumped to the absorber, where it reacts with SO_2 in the flue gas and is then returned to the holding tank. Slurry from the absorber holding tank is pumped to the venturi holding tank and from there to the venturi to scrub out fly ash. The slurry containing the fly ash returns to the venturi holding tank, from which it is pumped to the sludge disposal area for final treatment. Other designs have only one holding tank for the venturi and absorber.

2.2.6 Sludge Disposal

Sludge disposal can require 200,000 m^2 at a small plant and as much as 4,000,000 m^2 at a large plant. Disposal practices are very site specific. A power plant in an arid location might pump the sludge into an unlined pond, allowing the water to evaporate or seep into the ground. In an area where surface runoff or leaching could be a problem, the sludge sometimes is dewatered before being pumped into a lined pond. The water is returned to the system or purged after treatment to reduce chloride ions in the slurry. Plants located in areas where land is relatively expensive dewater the sludge to at most 20 percent liquid level by using clarifiers, thickeners, and vacuum filters and then fix the sludge by adding a proprietary compound. Fixation is necessary to allow the sludge pond to be used as a construction site at a later date. A totally closed system where no water is purged into a nearby stream or river has been achieved at the Sherburne County Station, Becker, Minnesota. Closed-loop systems are more subject to chloride ion concentration buildup in the slurry, especially when coal containing chloride is burned.

2.3 OPERATING PARAMETERS

2.3.1 Chemical Parameters

The limestone addition rate in the United States is 1.1 to 1.7 times stoichiometric requirements. In contrast, the rate of addition in Japan is 0.95 to 1.2 of the stoichiometric requirement at limestone/gypsum systems. Control of pH to close tolerances is necessary in limestone systems to prevent scaling. One system reportedly controls to within 0.01 pH of the optimum.* Straight-line (unvarying) pH control is one acceptable method of control. This is especially necessary if the boilers have wide variations in load. When the load changes, the liquid rate must be changed to compensate for the variation in gas flow or scaling could occur. The pH normally ranges from 7.0 to 7.5 in fresh slurry, from 5.2 to 6.2 in the recirculating slurry of the SO_2 absorber, and from 5.2 to 6.5 in the venturi scrubber.

2.3.2 Physical Parameters

Liquid-to-gas ratios in the venturi scrubber vary from 1.3 to 2.3 liters/Nm^3 when high particulate removal is desired. Flue gas velocities at the venturi throat vary from 37 to 60 m/s and pressure drops across the venturi from 1.5 to 3.7 kPa. If the venturi scrubber is designed only to

* Set point of 5.555 is carefully maintained at the primary venturi scrubber inlet at this plant.

cool and humidify the flue gas, and not to remove particulates, all of the above parameters would have a lower range.

Liquid-to-gas ratios in the SO_2 absorber vary from 3 to 11 liters/Nm^3. Flue gas velocities in the scrubber vary from 2 to 3 m/s and pressure drops across the SO_2 absorber from 500 to 1800 Pa.

Flue gas velocities in a Chevron type demister average around 6 to 8 m/s. The optimum flue gas velocity in horizontal Chevron type demisters is 3.5 m/s. Although increasing the velocity increases the mist removal rate, it also increases the entrainment of mist before it can leave the demister. Pressure drop across the demister varies from 100 to 500 Pa.

Reheating of the flue gas to between 17° and 44°C is required to prevent condensation in the gas. The energy necessary to reheat the gas is approximately 1100 J/kg of flue gas/°C of reheat.

Absorber hold tank retention times of 8 to 15 min are required to insure proper mixing of fresh limestone with scrubber effluent. Retention time in the venturi hold tank tends to be longer. Sludge hold tanks, which supply the sludge disposal system, have a retention time of 10 to 20 h.

A typical thickener on a small utility boiler is 20 m in diameter and 5 m high. On a very large utility boiler, it can be 50 m in diameter. The thickener increases the sludge solids content from 10 to 40 percent. Typical thickener overflow rates of approximately 0.12 m^3/m^2 of surface area per hour are used.

3.0 CURRENT STATUS, ASSESSMENT, AND PLANS

Limestone/sludge and lime/sludge systems are equally popular in the United States. The only limestone processes in operation in Japan are limestone/gypsum systems, and only one limestone/sludge system is still operational in the United Kingdom. Thirteen units are in operation in the United States with a total of 5640 MW; 18 are under construction (7785 MW) and another 13 are planned (5813 MW). The limestone/sludge process is viable and is currently a common choice for utilities in the United States. The long-term trend for this system will be determined by its ability to operate reliably and by the advancements made on FGD systems. Short-term trends for the process are definitly upward; its main competition is from the similar lime/sludge system.

The chemistry of this process is relatively well defined; however, mechanical problems still persist at certain facilities. These include erosion of pipes and pumps, fan vibration, poor pH control, failure of equipment linings, etc. These problems were largely due to inadequate design and poor process control. They are being solved

after several years of operating experience. Proper initial design and routine cleaning are effective preventive measures.

Because of its requirements for a sludge disposal area and large quantities of limestone, the limestone sludge system is suited for areas with a low population, low land cost, and available limestone. Wastewater discharge regulations could require additional treatment of sludge pond overflow, and strict solid waste regulations would require lined ponds to prevent infiltration into ground water. Location in mountainous areas is possible with a sludge pond similar to that at the Bruce Mansfield plant in Shippingport, Pennsylvania,* where a 120-m-high dam was built in a ravine. The ravine is slowly being filled with sludge. This process is not generally suited to areas without a sludge disposal site, unless the sludge can be piped to a remote site or a large area such as a bay or flood plain is available for filling with stabilized sludge.

Table 1 summarizes the status of limestone/sludge systems. The collection efficiency and availability ranges on this table refer only to the surveyed systems, whereas all other information refers to all limestone/sludge systems as of December 1977. Table 2 presents important characteristics of each surveyed facility. More detailed information can be found in the questionnaires in Appendix A.

* A lime/sludge system.

Table 1. SUMMARY OF LIMESTONE/SLUDGE SYSTEMS

All systems	
Total number of systems in operation	13
Total number of systems built and operated	23
Total number of systems surveyed	3
Year first placed in commercial service	1933
Number of utility systems using process	13
Total MW of these facilities now in operation	5640
Number of industrial combustion systems	0
Surveyed Systems	
Ranges of average SO_2 removal efficiencies[a], %	57-92
Range of fly ash removal efficiency of FGD, %	98-99
Range of average availability factors[b], %	88-94

[a] St. Clair has achieved 91%.

[b] See appendix.

Table 2. STATUS OF SURVEYED INSTALLATIONS LIMESTONE/SLUDGE PROCESS

Name of plant and company	Location	Size, MWe	Fuel type	Characteristics		Flue gas treated from boiler		Year FGD system started	SO_2 removal efficiency, %	Disposition of end products	Energy required % total input	Avg. % availability
				% S	Heat value 10^6 J/kg	Nm^3/s	% of total					
La Cygne Kansas City Power & Light	La Cygne Kansas	820	Coal	5.4	21.9	921.7	100	1973	80	Unlined pond on site	2.9[a]	91
Cholla Arizona Public Service Co.	Joseph City Arizona	115	Coal	0.55	23.9	175.9	100	1973	58.5	Unlined pond on site	1.4[c,d]	87.7 (12/76-5/77)
Sherburne County Northern States Power Co.	Becker Minnesota	710	Coal	0.8	19.3	1049	100	1976	57.1	Ponding	4[d,e]	94 (Recently)

[a] In addition 3% reheat required.

[b] System has two separate parallel modules. Packed module removes 92% SO_2; other module is a flooded disc scrubber for particulate removal and removes about 25% of the SO_2. See Appendix A for further details.

[c] In addition 0.8% reheat required.

[d] Estimated; includes particulate control.

[e] In addition 1.1% reheat required.

4.0 RECENT TECHNOLOGICAL DEVELOPMENTS AND SOLUTIONS TO PROBLEM AREAS

Because the low initial investment and operating costs of limestone scrubbing make it a popular choice in the utility industry, a great deal of effort has been applied to improve the technology and solve the problems associated with it.

4.1 RECENT TECHNOLOGICAL DEVELOPMENTS

A significant new development in lime and limestone systems has resulted from the discovery that the presence of Mg ion in the absorber slurry reduces scale, and increases SO_2 removal rate.* The mechanism postulated is that $MgSO_3$ reduces mass transfer resistances both in the liquid film and at the solid surface interface.

The steps in the reaction begin with the undissociated ion pair $MgSO_3$ and sulfurous acid in the scrubber.

$$H_2SO_3 + MgSO_3 \rightarrow Mg^{++} + 2HSO_3^- \qquad (11)$$

In the presence of calcium ions, $MgSO_3$ is regenerated in the absorber hold tank by

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* These investigations were conducted in the U.S. at TVA's Shawnee Pilot Plant, Louisville Gas and Electric Co.'s Paddy's Run Plant, and by Combustion Engineering Co.

$$Mg^{++} + 2HSO_3^- + CaCO_3 \rightarrow MgSO_3 + Ca^{++} + SO_3^{=} + CO_2 + H_2O \quad (12)$$

This reaction supplies calcium ions (see equations 8 and 10 in Section 2) and results in the final disposable product.

The presence of $MgSO_3$ reduces scaling in the absorber because the regeneration (equation 12) occurs in the absorber hold tank and not in the absorber. The contents of the absorber hold tank are fed to the absorber. The SO_2 reacts with the $MgSO_3$ species in solution and forms a soluble product. The slurry returns to the absorber hold tank and is mixed with makeup limestone slurry to regenerate the $MgSO_3$ species. The concentration of $CaSO_3 \cdot 1/2H_2O$ and $CaSO_4 \cdot 2H_2O$ does not build up to the 130 to 140 percent supersaturation levels that occur in systems without magnesium and, therefore, does not precipitate out in the absorber. This reduces the solids content of the slurry in the absorber section.

Gypsum yields are higher because reactions 13 and 14 proceed much faster than reaction 15.

$$MgSO_3 + 1/2\ O_2 \rightarrow MgSO_4 \quad (13)$$

$$CaSO_3 + 1/2\ O_2 \rightarrow CaSO_4 \quad (14)$$

$$MgSO_4 + CaSO_3 \rightarrow MgSO_3 + CaSO_4 \quad (15)$$

The $MgSO_4$ formed readily regenerates in the presence of $CaCO_3$, using the same mechanism shown in equation 12. The magnesium ion formed, $MgSO_3$, stays in solution for return to

the absorber. Gypsum is the more favorable disposal product because its crystalline structure allows closer packing than does calcium sulfite hemihydrate.

A second development in limestone/sludge systems is forced oxidation of the sludge in the absorber hold tanks; it is used at the Sherburne County Station. This is not a new development worldwide, since the Japanese have been using this idea in all their limestone systems to produce gypsum. In a limestone/sludge system, forced oxidation reduces scaling and produces a more acceptable sludge (it dewaters more easily, packs more closely for a more compact landfill and provides a better construction base).

4.2 SOLUTION TO PROBLEM AREAS

Three methods recently developed to prevent or reduce scale in the absorber include soluble magnesium addition, gypsum crystal addition, and unsaturated system operation.

The addition of 3 to 5 percent $MgSO_3$, MgO, $MgCO_3$, or $Mg(OH)_2$ not only reduces scaling but also increases the SO_2 removal rate and yields more gypsum ($CaSO_4 \cdot 2H_2O$) as opposed to $CaSO_3 \cdot 1/2\ H_2O$. Gypsum crystals provide suitable crystallization sites where $CaSO_4$ can precipitate in preference to absorber walls and internals. Fresh seed crystals are supplied while the oversized crystals are removed. Unsaturated system operation simply means that the $CaSO_3 \cdot 1/2H_2O$

and $CaSO_4 \cdot 2H_2O$ never become supersaturated in the scrubber, so they cannot precipitate and cause scaling.

Spray washes and soot blowers have been used to reduce scaling in many places upstream and downstream from the absorber, especially to protect reheat coils and demisters.

Excess chloride ion concentration in the slurry has caused corrosion in downstream equipment (especially reheat coils) and may cause waste water disposal problems. Chlorides in the scrubbing solution occur primarily from the combustion of chloride bearing fuel, and to lesser extent from chloride in the raw water and limestone. Chloride concentrations in the scrubber liquor increase with the amount of liquor recycled. These problems can be reduced by 1) using a prescrubber and keeping that liquid stream separate from the SO_2 absorber streams, 2) designing for chloride corrosion resistance, and 3) increasing the system water purge rate. Depending on waste water discharge regulations, the purge stream may require treatment.

The potential effects of waste water discharge or leaching into ground water from sludge ponds are not yet known and would vary widely with plant location. Waste water treatment and increased waste recirculation may be required to eliminate these potential problems.

5.0 COST

Table 3 presents available cost data on limestone/sludge FGD systems. The costs have been escalated to January 1976 initiation of plant construction using a plant cost index from Chemical Engineering (1957-59 = 100, Jan. 1976 = 187.1). The plant cost index provides a ratio of the 1976 cost of plant construction with the cost during the actual construction.

Kansas Power and Light provided itemized capital costs and annual fixed charges, but annual operating cost figures were limited to maintenance and raw materials. Arizona Public Service Co. provided only total capital costs. Northern States Power Co. (NSPC) provided capital costs and annual operating costs. The total cost at NSPC includes improvements to the ESP.

Because available cost data were very limited, some annual costs were estimated.* Reported costs were used

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* Ponder, T.C., L.V. Yerino, V. Katari, Y. Shah, and T.W. Devitt. Simplified Procedures for Estimating Flue Gas Desulfurization System Costs. Industrial Environmental Research Laboratory, Research Triangle Park, N.C. EPA-600/2-76-150 U.S. Environmental Protection Agency, Washington, D.C., June 1976.

where available in the estimating procedure; otherwise the following costs were assumed:

Electricity	25 mills/kWh
Limestone	$16.50/Mg
Labor	$10/h

The life of an FGD system was assumed to be 20 years; interim replacement, taxes, insurance, and capital charges amounted to 0.1365 of the total 1976 capital cost.

Table 3. COST DATA OF INDIVIDUAL INSTALLATIONS FOR THE LIMESTONE/SLUDGE FGD SYSTEM

Company name Plant name Location	Kansas City P&L LaCygne LaCygne, Kans. USA	Arizona PSC Cholla Joseph City, Ariz. USA	Northern States Power Sherburne Becker, Minn. USA
1. Reported capital costs, $	45,642,000[a]	10,935,000[b,c]	60,000,000[d]
Year	1973	1973	1975
Cost inflated to 1976	58,466,000	12,878,500[c]	63,190,000
$/kW	71.3	73.9	57.6
2. Reported annual costs, $			
Total variable costs	4,380,000[b,c]	1,532,000[b,c]	8,646,000[b,c]
Fixed charge factor, %	15.38	18.74	11.7
Total fixed costs	8,994,000	2,414,000[b]	7,020,000[f]
3. Boiler operating hours	5048/1975	8500/1974	7887
Capacity factor	0.326/1975 0.426/1976	0.9/1974, 1975 0.85/1976, 1977	0.677
Generated MWh	3060043	433243[b]	4210669
4. Reported cost per kWh, mills/kWh	4.6	3.79	4.68[b]
Total cost, mills/kWh[e]			
4000 h	3.80	6.91	4.22
8000 h	2.43	4.29	2.88
Fixed cost	2.94	4.52[b]	2.20
Variable costs	1.43	2.87[b]	2.48

[a] Include $11,000,000 modifications.

[b] FGD system only. Estimated where actual data are not available.

[c] Cost of sludge disposal included in capital cost.

[d] Units 1 and 2.

[e] Based on capacity factor of 100%.

[f] Annual estimate based on seven months of actual operations.

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APPENDIX A

APPENDIX A. QUESTIONNAIRE DATA ON THE LIMESTONE/SLUDGE FLUE GAS DESULFURIZATION PROCESS

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
1.	GENERAL DESCRIPTION			
1.1	Company	Kansas City Power and Light Company	Arizona Public Service Co.	Northern States Power Co.
1.2	Plant name	La Cygne	Cholla Power Generating Station	Sherburne County Generating Plant
1.3	Preparer's name and mailing address	R. Gerstle 11499 Chester Rd. Cincinnati, Ohio 45246	T. W. Day 11499 Chester Rd. Cincinnati, Ohio 45246	T.W. Day 11499 Chester Rd. Cincinnati, Ohio 45246
1.4	Principal plant products	Electrical power	Electric power	Electrical power
	Brief description of area surrounding plant site and factors for choice of FGD system	Located in a fairly flat agricultural area; the FGD system was built into the overall system by B&W with ample limestone and sludge disposal space available	Located in a relatively flat, arid region near Joseph City, Arizona. The FGD system removes SO_2 by use of two towers which handle 50% each (one packed, one unpacked). The unpacked tower does not circulate absorbent slurry	Located in a rural area adjacent to the Mississippi River. Selection was made as most economical choice in 1972
1.5	Plant location	La Cygne, Kansas	Joseph City, Arizona	Becker, Minnesota
1.6	STATION CAPACITY			
1.6.1	Total boiler generating capacity MW number of boilers	820/1	115/1	1440/2
1.6.2	Capacity served by FGD system, MW	820	115	1440
	Amount of flue gas treated, m^3/h	N.A.	N.A.	N.A.
	% of boiler flue gas treated by FGD system	100	100	100
	Number of boilers served	1	1	2 (each has an FGD system)

N.A. - Not available.
Nm^3/h - m^3/h (0°C and 101.325 Pa)

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
1.7	TYPE OF FGD SYSTEM	Limestone/sludge	Limestone/sludge	Limestone scrubbing/sludge
1.8	Number of scrubber trains in parallel	8	2	12 per unit
1.9	FGD system installed on new or existing boiler	New	Existing	New
1.10	STATUS OF FGD SYSTEM operational or under construction, date started	Operational, February 1973	Operational, October 1973	Unit 1 - Operational, March 1976 Unit 2 - Operational, January 1977
2.	BOILER DATA			
2.1	Boiler identification number	La Cygne No. 1	Cholla No. 1	No. 1, No. 2
2.2	Maximum continuous heat input, MW	2248	325.9	N.A.
2.3	Max. cont. net generating capacity, MW	820	124	700/Boiler
2.4	Flue gas flow rate, m^3/h temperature at induced draft fan, °C	4,690,800 140	885,600 135.6	4,519,440 77.2
2.5	Boiler manufacturer	Babcock and Wilcox	Combustion Engineering	Combustion Engineering
2.5.1	Fuel type	Coal	Coal	Subbituminous coal
2.5.2	Firing configuration	Cyclone fired	Pulverized coal fired	Tangential (8) at 7 levels
2.6	Year placed in service	1973	1962	Unit 1 - May 1976 Unit 2 - April 1977
2.7	Type service	Base load	Base load	Base load
2.8	Stack height, m	213	75.8	198.12
2.8.1	Flue gas exit velocity, m/s	N.A.	N.A.	27.43
2.9	Average boiler operation, h/yr	5048/1975	N.A.	7887/5-1-76 to 4-30-77 unit #1
2.10	Average boiler capacity factor	0.326/1975 0.425/1976	N.A. N.A.	0.677

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
2.11	COAL COMPOSITION			
2.11.1	Lower heating value, kJ/kg	21,878	23,911	19,289 (HHV)[a]
2.11.2	Sulfur content, %	5.39	0.55	0.8
2.11.3	Ash content, %	24.36	10.4	9.0
2.11.4	Chloride content, %	0.027	0.01-0.04	N.A.
2.11.5	Moisture, %	9.07	14.77	25.0
2.12	OIL COMPOSITION	N.A.	N.A.	N.A.
2.12.1	Grade/heating value, kJ/kg			
2.12.2	Sulfur content, %			
2.12.3	Ash content, %			
2.12.4	Chloride content, %			
2.13	PARTICULATE REMOVAL EQUIPMENT NOT PART OF FGD SYSTEM	None		None
2.13.1	Type		Mechanical	
2.13.2	Manufacturer		Research-Cottrell	
2.13.3	Efficiency, % removal		75	
2.13.4	Emission rate, mg/Nm^3		4600	

[a] (HHV) = Higher Heating Value

(continued)

APPENDIX A (continued)

	BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
3. EMISSION REGULATIONS			
3.1 ATMOSPHERIC EMISSIONS			
3.1.1 SO_2, ng/kJ	0.645	0.43	0.4127
3.1.2 Particulate, ng/kJ	0.056	0.084	0.037
3.1.3 NO_x	Subject to National Ambient Standards of 0.5 ppm NO_2 annual average	None	N.A.
3.1.4 Other	N.A.	None	N.A.
3.1.5 Legal basis	State of Kansas except NO_x is Federal Standard	State of Arizona Department of Health	Minnesota Pollution Control Agency
3.2 RESTRICTIONS APPLICABLE TO LIQUID OR SOLID WASTES, LEGAL BASIS	N.A.	N.A.	N.A.
4. FGD SYSTEM INFORMATION			
4.1 Process name	Limestone/sludge	Limestone/sludge	Limestone scrubbing
4.1.1 Supplier or design company	Babcock and Wilcox	Research-Cottrell	Combustion Engineering
4.1.2 WHY WAS THIS SYSTEM CHOSEN?	B&W responsible for installing power boiler. SO_2 and particulate removal system was incorporated into original power plant design	N.A.	Economy - it was the best available technology (1972)
4.1.3 PROCESS DESCRIPTION	See Figure A	See Figure B	See Figures C and D

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
4.2	SO_2 SCRUBBING AGENT			
4.2.1	Name	Limestone	Limestone	Limestone
4.2.2	Chemical composition	$CaCO_3$ $MgCO_3$ Silicates Moisture and gangue	CaO MgO $CaCO_3$ Silica	$CaCO_3$
	Components, % by weight	$CaCO_3$, 85-93 $MgCO_3$, 2.5 (max) Silicates, 5-7 Moisture and gangue, 8 (max)	$MgCO_3$, 0.5 (max) $CaCO_3$, 95 (min) Silica, 1.0 (max)	$CaCO_3$, 96
4.2.3	Stoichiometric requirement	2.0	1.1	1.3
4.2.4	Addition rate	110.4 (ℓ/s) @20% solids	95% utilization	N.A.
4.2.5	Particle size, mm	90% less than 1.80	70% less than 1.80	80% less than 1.41
4.3	REGENERATION AGENT	None	None	None
4.3.1	Name			
4.3.2	Composition			
4.3.3	Stoichiometric requirement			
4.3.4	Addition rate			
4.3.5	Particle size			
4.4	SALABLE PRODUCT			
4.4.1	Name			
4.4.2	Chemical composition Components, % by weight			
4.4.3	Amount generated/year, tons/yr			
4.4.4	Sales potential			

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
4.4.5	BY-PRODUCT RECOVERY PROCESS	None	None	None
	Name			
	Vendor			
	Process description			
4.4a	Intermediate product composition			
4.5	BY-PRODUCT NO. 2	None	None	None
4.6	WASTE STREAMS			
4.6.1	Type of waste	Sludge	Sludge	Slurry
	% water	85-90	84	88
4.6.2	Amount generated in one hour at full load, m^3/h	185	N.A.	N.A.
4.6.3	Disposal method	On-site pond (unlined)	On-site pond (unlined)	Ponding
4.6.4	Disposal site and distance from plant, km	0.8	N.A.	0.8
4.6.5	Potential effects on environment from sludge disposal	Pond is not lined - no known effect	N.A.	None
4.7	SLUDGE FIXATION PROCESS	None	None	None

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
4.8	FGD EQUIPMENT DATA			
4.8.1	FIRST SCRUBBER			
4.8.1.1	Type	Venturi	Venturi	Venturi
4.8.1.2	L/G[a] ratio, ℓ/Nm^3	1.6	1.37	2.3
4.8.1.3	Gas velocity through absorber or scrubber, m/s	39.4-44.5	N.A.	60
4.8.1.4	Absorbent (adsorbent) flow m^3/h	107.7 (for 7 modules)	N.A.	21.5
4.8.1.5	Gas flow entering scrubber, m^3/h	78,300	5940	5664 (each module)
4.8.1.6	Gas temperature, °C	140	136	154
4.8.1.7	Gas composition			
	SO_2 in + out, ppm	4530 + 902	N.A.	700 + 400
	% removal	80	N.A.	57
	Particulate in + out,	4.26 mg/kJ + 0.08 mg/kJ	A) 4.824 + 0.0201 g/Nm^3 99%	7.255 + 0.0967 g/Nm^3
	% removal	98.2	B) 6.135 + 0.0244 g/Nm^3	99
	NO_x in + out, ppm	N.A.	N.A.	N.A.
	CO_2 in + out, ppm	N.A.	N.A.	N.A.
	Other in + out	N.A.	N.A.	N.A.
4.8.1.8	Material of construction	316L stainless	N.A.	Carbon steel
4.8.1.9	Type of lining	Ceramic (Kaocrete)	None	316L and Ceilcote
4.8.1.10	Adsorbent and sand losses	N.A.	N.A.	N.A.
4.8.1.11	Number of stages	N.A.	N.A.	1
4.8.1.12	Packing type and composition	N.A.	N.A.	None

[a] Liquid-to-gas ratio.

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
4.8.2	SECOND SCRUBBER			
4.8.2.1	Type	Perforated plate tower	Wetted film contactor	Marble tower
4.8.2.2	L/G ratio, ℓ/Nm^3	3.6	6.02 for A Module, 0 for B; 3.01 overall	1.35
4.8.2.3	Gas velocity through absorber or scrubber, m/s	2.54	2.09	3.302
4.8.2.4	Absorbent (adsorbent) flow, m^3/h	246.9 (for 7 modules)	N.A.	7.68
4.8.2.5	Gas flow entering scrubber, m^3/h	68580	5400	5664
4.8.2.7	Gas composition			
	SO_2 in + out	4.3 ng/kJ + 0.86 ng/kJ	A) 417 ppm + 34 ppm = 92% 58.5%	700-875 + 350 ppm
	% removal	80	B) 409 ppm + 357 ppm = 25% (overall)[a]	50-60
	Particulate in + out	3.3 ng/kJ + 0.06 ng/kJ	N.A.	0.0967 + 0.0967 g/Nm^3
	% removal	98.2	N.A.	N.A.
	NO_x in + out, ppm	N.A.	N.A.	N.A.
	% removal	N.A.	N.A.	N.A.
	CO_2	N.A.	N.A.	N.A.
	Other	N.A.	N.A.	N.A.
4.8.2.8	Material of construction	316L	316L	Carbon steel
4.8.2.9	Type of lining	None	None	Ceilcote
4.8.2.10	Number of stages	2	N.A.	1
4.8.2.11	Packing type and composition	None	Polypropylene	2.06 cm glass marbles

[a] Absorber is not packed and has no slurry circulation.

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
4.8.3	CLEAR WATER TRAY			
4.8.3.1	Type	316L 11 gauge 3.5 cm holes	None	None
4.8.3.2	L/G ratio, ℓ/Nm^3	N.A.	N.A.	N.A.
4.8.3.3	Source of water	Original pond water presently well water	N.A.	N.A.
4.8.4	DEMISTER			
4.8.4.1	Type	Chevron	N.A.	Chevron
4.8.4.2	Number of passes (stages)	2	2	2
4.8.4.3	Material of construction	Fiberglass	Polypropylene	Fiberglass
4.8. .4	Method of cleaning	Water spray	Water spray	Wash blowers
4.8.4.5	Flow rate during cleanings, m^3/h	Overspray - 8.1 Underspray - 0.48	0.46	N.A.
4.8.4.6	Frequency and duration of routine cleaning	Continuous overspray	N.A.	Once daily
4.8.5	REHEATER			
4.8.5.1	Type	5-Steam and supplemental hot air 3-Steam only	Shell and tubes	In-line hot water finned tube
4.8.5.2	Heat load, kW	N.A.	2340	38.65
4.8.5.3	Heat transfer surface area, m^2	N.A.	N.A.	964
4.8.5.4	Temperature of gas in, °C out, °C	49 88	50 72	55 77
4.8.5.5	Reheater materials of construction	316L stainless	316L S.S.	Carbon steel

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station		COMBUSTION ENGINEERING Sherburne County Generating Plant
			Module A	Module B	
4.8.6	SCRUBBER TRAIN PRESSURE DROP, mbar				
4.8.6.1	First scrubber	16-23	33.9	33.9	0.00323
4.8.6.2	Second scrubber	16	0.3	0.0	0.00162
4.8.6.3	Clear water tray	3	N.A.	N.A.	N.A.
4.8.6.4	Demister	0.5	0.5	0.5	N.A.
4.8.6.5	Reheater	9.4	6.5	6.5	1.3
4.8.6.6	Ductwork	10.4	7.8	7.8	5.2
4.8.6.7	Total FGD system	52-62.6	49.0	49.0	52-57
4.8.6.8	I.D. fan	N.A.	N.A.	N.A.	N.A.
4.9	SYSTEM MAKEUP WATER ADDED, m^3/h	266	9.23		19.23
4.9.1	Water added per mole of SO_2 removed	5.38 t/MW	1.461 m^3/g mol		N.A.
4.9.2	Source of makeup water	Cooling pond	Well		River water and pond return
4.9.3	Where is water added	Demister section	Demisters and pump seals only		To modules
4.10	BYPASS SYSTEM				
4.10.1	Can flue gas be bypassed?	No	Yes		No
4.10.2	Height of gas discharge when bypassed, m	None	N.A.		None
4.11	SLURRY DATA, pH, % solids by weight				
4.11.1	Fresh slurry to scrubber	7.5/20	Varies		N.A./4.0
4.11.2	Recirculating slurry	5.5/8-10	5.0/15		N.A./10.0
4.11.3	Waste slurry	5.5/8-10	5.0/15		N.A./5.0

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
4.12	SPENT SLURRY SYSTEM	None	None	
4.12.1	Clarifiers			
4.12.1.1	Number			1 in service; 1 spare
4.12.1.2	Diameter, m			48.77
4.12.2	Solid separation			
4.12.2.1	Type			
4.12.2.2	Cloth area, m^2			
4.12.2.3	Capacity (wet cake), tons/h			
4.13	SPACE REQUIRED, EXCLUSIVE OF SLUDGE DISPOSAL AREA, m^2	None	None	None
4.14	PERSONNEL (man-hours/year)			
4.14.1	Operating	N.A.	N.A.	N.A.
4.14.1.1	Specialists	N.A.	N.A.	14,560[b]
4.14.1.2	Unskilled	60,000	N.A.	41,600[b]
4.14.2	Maintenance and repair	12,000	N.A.	31,200[b]
4.15	ENVIRONMENTAL LOAD			
4.15.1	Waste water treatment process	None	None	Blowdown to settling basin then to river
4.15.2	Concentrations	N.A.	N.A.	6000 mg/ℓ total dissolved solids[c]
4.15.3	Appearance of flue gas discharge - any mist problems?	No	No	Opacity 40-45%

[a] Number of people will be reduced at some future date.

[b] Based on normal 40 hour work week for 52 weeks, for 7, 20, and 15 men respectively.

[c] Ca-500 mg/ℓ, SO_4-1500 mg/ℓ, SO_3-0 mg/ℓ.

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
4.16	FGD SYSTEM OPERATION			
4.16.1	% of boiler load FDG can operate	Full range	Full range	Full range
4.16.2	Lag time	N.A.	N.A.	No lag time
5.	ACTUAL COSTS FOR TOTAL FGD INSTALLATION, year	1973	1973	1975
5.1	CAPITAL COSTS, $			
5.1.1	Scrubber	19,300,000	N.A.	N.A.
5.1.2	Absorbent/regeneration system	4,900,000	N.A.	N.A.
5.1.3	Sludge disposal system	3,200,000	N.A.	N.A.
5.1.4	Site improvements	260,000	N.A.	N.A.
5.1.5	Land, roads, tracks, substation	82,000	N.A.	N.A.
5.1.6	Engineering costs	1,600,000	N.A.	N.A.
5.1.7	Contractor's fee	1,200,000	N.A.	N.A.
5.1.8	Interest during construction	4,100,000	N.A.	N.A.
	Construction period, mo	50	18	N.A.
5.1.9	License fees	N.A.	N.A.	N.A.
5.1.10	Other	Subsequent modification 11,000,000	N.A.	N.A.
5.1.11	Total, $/kW	45,642,000	6,500,000 (includes start-up expenses)	N.A.
		55	57	44

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
5.2	ANNUAL COSTS, $			
5.2.1	Interest	3,651,000 (est. @ 8%)	N.A.	N.A.
5.2.2	Depreciation	3,042,800 (15 years)	N.A.	N.A.
5.2.3	Insurance and taxes	242,000	N.A.	N.A.
5.2.4	Total fixed costs	6,935,000 (est.)	N.A.	N.A.
5.2.5	Labor and overhead Average man-hour cost cost/year	Labor (O&M) 501,000 (total for 1976)	N.A.	N.A.
5.2.6	Raw material breakdown	Limestone Materials	Limestone Transportation	Limestone
	Unit cost Annual cost	2.94/Mg N.A. 1,183,000 105,500	19.20-23.50 7.07-15.58 N.A. N.A.	375,000 @ 11/Mg N.A.
5.2.7	Utilities, unit cost, annual costs		N.A.	N.A.
	Electricity Water Steam Fuel	8.8 mills/kWh N.A. N.A. N.A.		
5.2.8	Maintenance cost/year	See Sec. 5.2.5	N.A.	Labor - 330,000 Supplies - 670,000
5.2.9	Other costs, list	N.A.	Coal - 0.99/GJ (levelized)	N.A.
5.2.10	Total variable cost/year	1,790,000	N.A.	N.A.
5.2.11	Total annual cost	8,725,000	N.A.	N.A.
5.3	WASTE DISPOSAL COST, $	N.A.	N.A.	(A) Operating 1) Labor (one 8 man/shift) 10,000 2) Supplies (one 64 man/shift) 1500 (B) Maintenance 1) Labor 66,000 2) Supplies 132,000
	Unit cost			
	Annual cost			
5.4	BY-PRODUCT CREDIT, $	None	None	N.A.
5.4.1	By-product 1			
5.4.2	By-product 2			

(continued)

APPENDIX A (continued)

		BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
5.5	NET ANNUAL COST, mills/kWh			N.A.
5.5.1	Last Year	4.6	2.2	
5.5.2	At maximum continuous rating	N.A.	N.A.	
5.5.3	Without FGD	7.58 mills	N.A.	
6.	ENERGY REQUIREMENTS, kW		N.A.	N.A.
	Pumps	N.A.		
	Fan	N.A.		
	Reheat	24,600		
	Reductant chemicals	N.A.		
	Other			
	Total	24,000 (total FGD system)		

(continued)

APPENDIX A (continued)

	BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
7 PERFORMANCE HISTORY: OPERATING PROBLEMS AND SOLUTIONS			
7.1 Scrubber system	Plugging and scale buildup requiring 3 men to clean one module each night. Very close control of pH has reduced this problem.	1) Erosion of fibercast "T" at pump discharge 2) Flow control valve liner suppose to be Teflon, but instead was carbon impregnated plastic 3) Mfg. defects on rubber lining 4) Scaling may become a problem on shaft and stuffing gland flange 5) Pluggage of small lines under reduced rates	1) Deposits of mud at the wet-dry interface were eliminated by modifying the steam blowers and increasing blowing frequency. 2) Spray nozzle pluggage caused by ineffective strainers, abandoned for new design reducing but not eliminating problem. 3) Pot covers failed in marble bed resulting in loss of marble. Annealing covers reduced failure rate. 4) Venturi rod erosion and mud build-up on nozzles. Wear plates were welded on, but only a temporary solution. 5) Failure of fiberglass flaked lining in first stage, wear plates installed temporary solution. 6) Pinhole failures in Unit 2 scrubbers. Minor plugging requiring periodic washing.
7.2 Demister	Scale buildup required frequent cleaning. Switched to water from cooling pond	Essentially none except for AP increase from about 0.13-0.18	
7.3 Reheater	Corrosion of type 304 steel; switched to 316L stainless steel	1) Vibrations due to transition duct solved by installing baffles 2) Tube bundle leaking was solved by replacing one bundle and installing an acid condensate draw-off baffle	Failures in the area of the return bends were due to field repair of shipping damage

(continued)

APPENDIX A (continued)

	BABCOCK AND WILCOX La Cygne	RESEARCH-COTTRELL Cholla Power Generating Station	COMBUSTION ENGINEERING Sherburne County Generating Plant
7.4 Fan	Vibrations and imbalance at start-up and requiring high pressure wash every 4-5 days.	Vibrations due to scaling while idle were solved by cleaning and sand blasting.	No problems
7.5 Sludge system	None	None	1) Plugging of piping and valves. 2) Plugging of dead-leg pipe. 3) Hydraulic and drainage problems with sludge transport lines. 4) Electrical malfunctions of valve operators. 5) Pump impellers must be replaced every 4000 h. Task force has been assigned to solve these problems.
7.6 Regeneration system	None	None	None
7.7 By-product system	None	None	None
7.8 Other	Duct corrosion due to acid runoff requiring Iconel 625 cladding.	Vertically mounted valves built up sediment in dead space and required valve modification and washout lines to be installed.	Duplex strainers on the outlet of the spray water pumps fail. Excessive maintenance manpower required.
7.9 Availability, %	84 - 1975 91 - 1976	87.7	94-95 recently

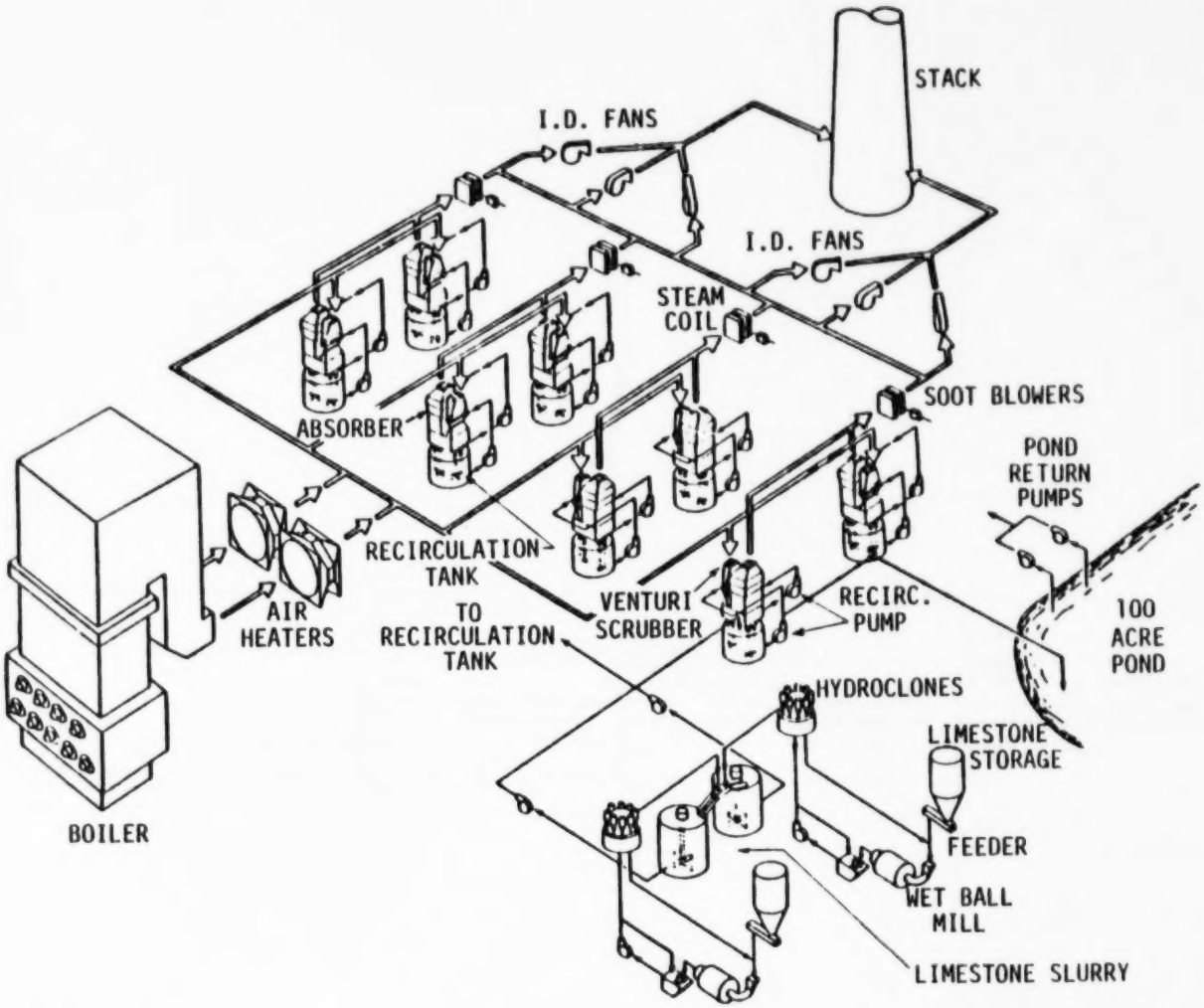

Figure A. Process flow diagram for the La Cygne No. 1 scrubbing system.

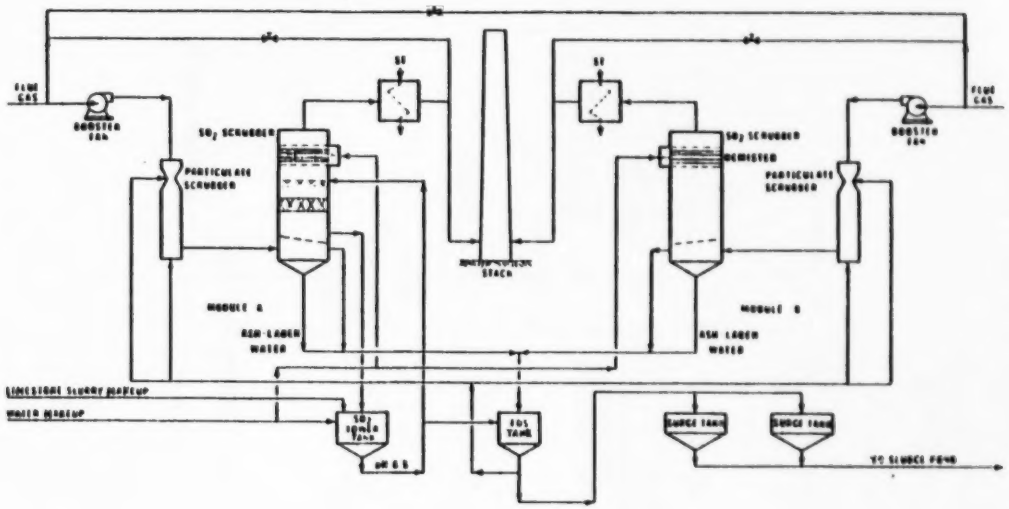

Figure B. Process flow diagram of the FGD system at the Cholla Power Plant.

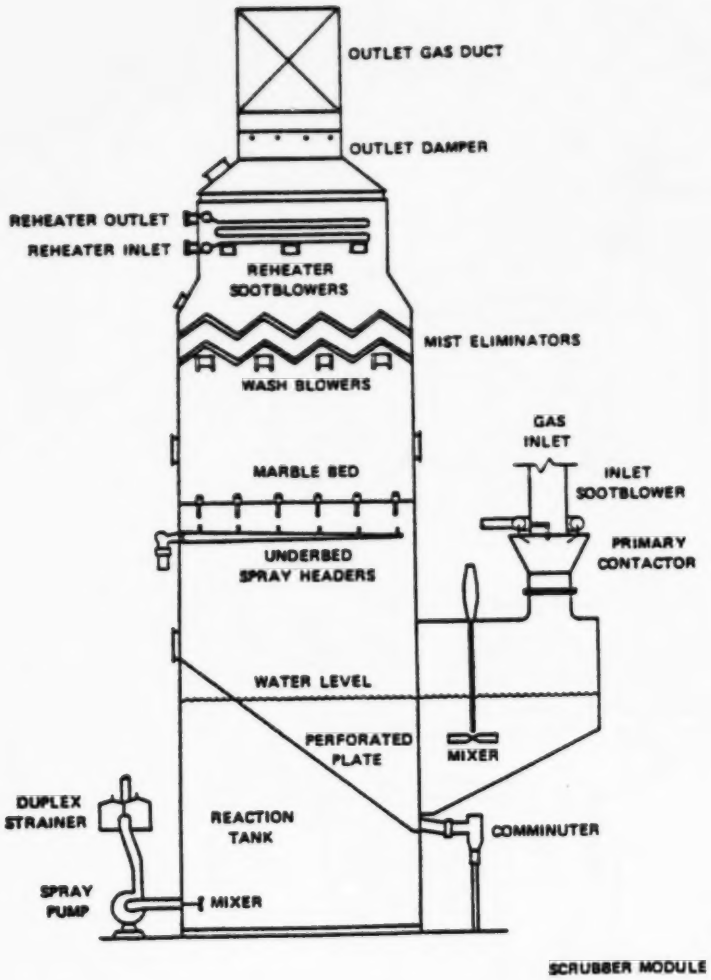

Figure C. Scrubber module at Sherburne.

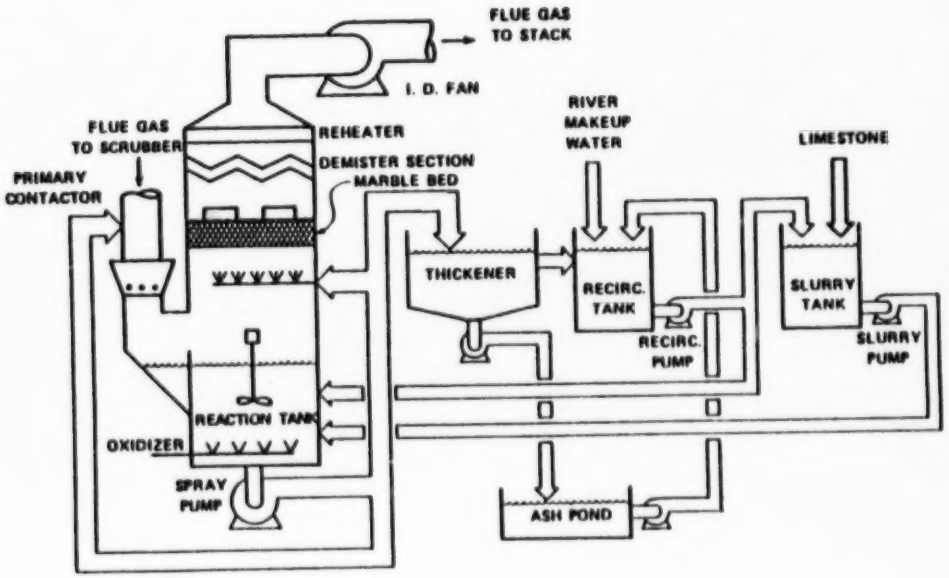

Figure D. Sherburne County wet scrubber system.

APPENDIX B

APPENDIX B

Availability Factor Computation

1. Divide boiler capacity by the number of modules and obtain MW/module = x

2. Multiply boiler capacity by number of hours during selected period (MW) = a

3. Add all down times due to module trouble for all modules during selected period = b

4. Add all down times due to boiler trouble or reduction in electricity demand for all modules during period = c

5. Availability factor = $\frac{[a - x\ (b + c)]\ 100}{a - x\ c}$ = %

APPENDIX C

APPENDIX C. CONVERSION FACTORS USED IN THIS STUDY

Multiply	By	To Obtain
ft	x 0.30480	m
ft^3	x 28.317	liter
Btu/lb	x 0.55554	kcal/kg
	x 2.32593	kJ/kg
Btu/h	x $0.29300 \cdot 10^{-3}$	kW
acfm	x 1.6992	m^3/h
$lb/10^6$ Btu	x 1.80005	mg/kcal
	x 0.42993	mg/kJ
gal/min	x 3.78541	liter/min
	x 0.22712	m^3/h
gal/1000 ft^3	x 0.13368	liter/m^3
ft^3/min	x 1.6992	m^3/h
kcal	x 4.1868	kJ
kcal	x $1.163 \cdot 10^{-3}$	kWh
scfm	x 1.60776	Nm^3/h
gr/ft^3	x 2.288	g/m^3
gr/scfm	x 2.4182	g/Nm^3
in. H_2O	x 0.2488	kPa
in. H_2O	x 2.54	mbar
gr	x 0.0648	g
ton (short)	x 1.9072	metric ton

1 MW corresponds to 3200 to 3500 m^3/h flue gas (coal)

1 scfm = 28.317 l (60°F / 14.7 psia)
(15.5°C / 760.28 torr)

26.796 l (0°C/760 torr) = 0.026796 Nm^3

1 SO_2 = 2.927 g/liter

MW = electric power generated unless other wise specified